

Top A_{FB} at the Tevatron vs. charge asymmetry at the LHC in chiral $U(1)$ flavor models with flavored Higgs doublets

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We consider the top forward-backward (FB) asymmetry at the Tevatron and top charge asymmetry at the LHC within chiral $U(1)'$ models with flavor-dependent $U(1)'$ charges and flavored Higgs fields, which were introduced in the Ref. [68]. In this model, one has to include the flavor changing couplings of the Higgs bosons as well as the Z' to the up-type quarks. The models could enhance not only the top forward-backward asymmetry at Tevatron, but also the top charge asymmetry at LHC, without too large same-sign top-quark pair production rates. Also the $m_{t\bar{t}}$ distribution at high $m_{t\bar{t}}$ show less deviations from the SM predictions. We identify parameter spaces for the $U(1)'$ gauge boson and (pseudo)scalar Higgs bosons where all the experimental data could be accommodated, including the case with about 125 GeV Higgs boson, as suggested recently by ATLAS and CMS.

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I. INTRODUCTION

The top quark has been one of the most promising channels to search for new physics beyond the Standard Model (SM). Among the observables involving the top quark, the top forward-backward asymmetry (A_{FB}^t) at the Tevatron has been paid much attention during the past few years, because it is the only quantity which has some deviations from the SM prediction in top quark sector. The CDF Collaboration announced that A_{FB}^t in the $t\bar{t}$ rest frame is (0.158 ± 0.074) in the lepton+jets channel [1], and (0.420 ± 0.158) in the dilepton channel [2], respectively. The combined result of them is (0.201 ± 0.067) , which is consistent with $A_{FB}^t = 0.196 \pm 0.060_{-0.026}^{+0.018}$ announced by the D0 Collaboration in the lepton+jets channel [3]. Very recently, the CDF Collaboration updated the results for A_{FB}^t in the lepton+jets channel with data of a luminosity of 8.7 fb^{-1} : $A_{FB}^t = 0.162 \pm 0.047$ [4]. This value is consistent with the previous measurements at CDF and D0. The SM predictions for A_{FB}^t are $0.072_{-0.007}^{+0.011}$ at the next-to-leading order (NLO) + next-to-next-to-leading logarithm accuracies [5, 6] and 0.087 ± 0.010 with NLO corrections for the electroweak interactions [7, 8], respectively. Therefore there is still about 2σ deviation between the SM prediction and experiments in the integrated A_{FB}^t at the Tevatron.

A number of new models have been proposed to account for the discrepancy in A_{FB}^t [9–69]. In order that those new models can accommodate the present data in the Drell-Yan, dijet production, flavor-changing-neutral-current (FCNC) experiments and so on, it is usually assumed that the new model has a large coupling only to the top quark. In general, it would be a challenging task to construct a realistic and consistent model with such a hierarchy in couplings. New models should also be anomaly-free and have proper Yukawa interactions. Otherwise there could be some hidden fields that might affect the physical observables we are interested in.

One of the most interesting models to account for A_{FB}^t

is a Z' model with an additional chiral $U(1)'$ symmetry, where only the right-handed (RH) up-type quarks in the SM are charged under the $U(1)'$ symmetry [67–69]. Such a chiral $U(1)'$ symmetry is inevitably accompanied with the modification of the Higgs sector in the SM, for instance, the addition of the multi-Higgs doublets charged under the $U(1)'$ symmetry. There are two reasons why we have to extend the Higgs sector.

First of all, all the SM fermions charged under chiral $U(1)'$ (such as top quark in Refs. [67, 68]) would be massless and so the model becomes unphysical without extra Higgs doublets charged under $U(1)'$. There is no limit where one can integrate out these $U(1)'$ -charged Higgs doublets assuming they are heavy. Secondly, the mass of the Z' boson could be generated through the $U(1)'$ breaking. One can achieve this either by the $U(1)'$ -charged Higgs doublets or $U(1)'$ -charged Higgs singlet. Without these Higgs fields that generate the Z' mass, the theory violates unitarity at high energy, and it loses its predictability. This situation is somewhat similar to the unitarity problem of the $W_L W_L \rightarrow W_L W_L$ or $f\bar{f} \rightarrow W_L W_L$ scatterings in the intermediate vector boson model. The unitarity of the model would be restored with the $U(1)'$ -charged Higgs fields (doublets and singlet). That is, additional Higgs fields are mandatory for generation of masses of the SM fermions charged under chiral $U(1)'$ and the $U(1)'$ gauge boson (Z') itself. The requirement for the extra Higgs fields is also true in the W' [11, 70], axigluon [47], flavor $SU(3)_{u_R}$ [25], and any other models if the SM fermions are chiral under new gauge interactions.

On the other hand, the gauge anomaly would exist in general if one introduces the flavor-dependent chiral $U(1)'$ symmetry. But it could be canceled by introducing extra fermions [67, 68]. We emphasize that in order to construct a realistic model for the chiral $U(1)'$ symmetry, one must take into account carefully the $U(1)'$ -charged Higgs fields and extra fermion fields in addition to the extra $U(1)'$ gauge field. It is important to realize that there is no proper limit where only light Z' survives with chiral couplings to the right-handed up-

type quarks. Literally speaking, the model by Jung, Murayama, Pierce and Wells [10] is not well defined as a gauge theory and not realistic, since the up-type quarks are all massless including top quarks. It is mandatory to extend the model by introducing extra Higgs doublets with nonzero $U(1)'$ charges, because the up-type quarks (including top quark) would be all massless without the extra Higgs doublets.

The Large Hadron Collider (LHC) is also called a “Top Factory” because a huge number of top-quark pair (larger than about 10^6) is expected to be produced at the LHC even before the technical shutdown at the end of this year. Thus new models proposed for resolutions of A_{FB}^t at the Tevatron including the flavor-dependent chiral $U(1)'$ model with flavored Higgs doublets [67, 68] could be tested at the LHC. For instance, the original Z' model is strongly constrained by the same-sign top-quark pair production at the LHC [71–74].

Another interesting observable at the LHC is the top charge asymmetry A_C^y defined by the difference of numbers of events with the positive and negative $\Delta|y|$ divided by their sum:

$$A_C^y = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}, \quad (1)$$

where $\Delta|y| = |y_t| - |y_{\bar{t}}|$ for the rapidities y_t and $y_{\bar{t}}$ of the top and anti-top quarks. Because the LHC is a symmetric collider under charge conjugation, A_{FB}^t cannot be defined at the LHC, unlike the Tevatron. However, at the LHC the top quark produced in the $q\bar{q} \rightarrow t\bar{t}$ process is statistically more boosted to the beam direction compared to the anti-top quark because the top quark follows the direction of the incident quark which has a larger longitudinal momentum. This difference could generate the charge asymmetry in Eq. (1). The theoretical estimate for A_C^y is about 0.01 at NLO [5], which is consistent with the empirical data $A_C^y = -0.018 \pm 0.028 \pm 0.023$ at ATLAS [75] and $A_C^y = 0.004 \pm 0.010 \pm 0.012$ at CMS [76] within uncertainties.

In the previous works [67–69], we considered only A_{FB}^t at the Tevatron and the same-sign top-quark pair production rate at the LHC in order to find parameter regions of the models which are consistent with the data available at that time. In this paper, we consider top charge asymmetry at the LHC within the same chiral $U(1)'$ model,

taking into account more stringent recent constraints on the same-sign top-quark pair production at ATLAS [72], and investigate if the model in Refs. [67–69] survives or not, and how we can test further these models at the LHC.

This paper is organized as follows. In Sec. II, we briefly review the chiral $U(1)'$ models with flavored Higgs doublets which were first proposed in Refs. [67, 68], with focus on the Lagrangian relevant to A_{FB}^t at the Tevatron and A_C^y at the LHC. In Sec. III, we discuss the phenomenology of our model at the Tevatron and LHC. Finally we conclude in Sec. IV.

II. CHIRAL $U(1)'$ MODEL WITH FLAVORED HIGGS DOUBLET

In this section we review the flavor-dependent chiral $U(1)'$ model with flavored Higgs doublets that were proposed in Refs. [67, 68]. Our model is an extension of a simple phenomenological Z' model with a large flavor changing neutral couplings in the u_R – t_R sector [10]. This Z' boson must be associated with some gauge symmetry if we work in weakly interacting theories. As a simple example we considered an extra $U(1)'$ symmetry [67, 68]. The Z' boson better be leptophobic to avoid the stringent constraints from the LEP II and Drell-Yang experiments. Furthermore, it would be very difficult to assign flavor-dependent $U(1)'$ charges to the down-type quarks and left-handed up-type quarks because it gives rise to dangerous FCNCs. Therefore we assigned flavor-dependent $U(1)'$ charges u_i ($i = u, c, t$) only to the right-handed up-type quarks while the left-handed quarks and right-handed down-type quarks have universal charges Q_L and d_R under $U(1)'$. For simplicity, we assign $Q_L = d_R = 0$.

Then, the Lagrangian between Z' and the SM quarks in the interaction eigenstates is given by

$$\mathcal{L}_{Z'q\bar{q}} = g' \sum_i u_i Z'_\mu \overline{U}_R^i \gamma^\mu U_R^i, \quad (2)$$

where U_R^i is a right-handed up-type quark field in the interaction eigenstates and g' is the coupling of the $U(1)'$.

After the electroweak symmetry breaking, we can rotate the quark fields into the mass eigenstates by bi-unitary transformation. The interaction Lagrangian for the Z' boson in the mass eigenstate is given by

$$\mathcal{L}_{Z'q\bar{q}} = g' Z'_\mu \left[(g_R^u)_{ut} \overline{u}_R \gamma^\mu t_R + (g_R^u)_{ut} \overline{t}_R \gamma^\mu u_R + (g_R^u)_{uu} \overline{u}_R \gamma^\mu u_R + (g_R^u)_{tt} \overline{t}_R \gamma^\mu t_R \right]. \quad (3)$$

The 3×3 mixing matrix $(g_R^u)_{ij} = (R_u)_{ik} u_k (R_u)_{kj}^\dagger$ is the product of the $U(1)'$ charge matrix $\text{diag}(u_{k=1,2,3})$ and a unitary matrix R_u , where the matrix R_u relates the RH up-type quarks in the interaction eigenstates and in the

mass eigenstates. The matrix R_u participates in diagonalizing the up-type quark mass matrix. In principle, the mixing matrix g_R could be complex, providing an additional source of CP violation in the right-handed up-

type quark sector. In this work, we assume it is real for simplicity. We note that the components of the mixing angles related to the charm quark have to be small in order to respect constraints from the D^0 - \bar{D}^0 mixing.

If one assigns the $U(1)'$ charge $(u_i) = (0, 0, 1)$ to the right-handed up-type quarks, one can find the relation $(g_R^u)_{ut}^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ *. This relation indicates that if the t -channel diagram mediated by Z' contributes to the $u\bar{u} \rightarrow t\bar{t}$ process, the s -channel diagram mediated by Z' should be taken into account, too.

As we discussed in the previous section, it is mandatory to include additional flavored Higgs doublets charged under $U(1)'$ in order to write down proper Yukawa interactions for the SM quarks charged under $U(1)'$ at the renormalizable level †. The number of additional Higgs doublets depends on the $U(1)'$ charge assignment to the SM fermions, especially the right-handed up-type quarks. In general, one must add three additional Higgs doublets with $U(1)'$ charges u_i [see Refs. [67, 68] for more discussions]. For the charge assignment $(u_i) = (0, 0, 1)$ we have two Higgs doublets including the SM-like Higgs doublet, while for $(u_i) = (-1, 0, 1)$ three Higgs doublets are required. The additional $U(1)'$ must be broken in the end, so that we add a $U(1)'$ -charged singlet Higgs field Φ to the SM. Both the $U(1)'$ -charged Higgs doublet and the singlet Φ can give the masses for the Z' boson and extra fermions if it has a nonzero vacuum expectation value (VEV). After breaking of the electroweak and $U(1)'$ symmetries, one can write down the Yukawa interactions in the mass basis. The Yukawa couplings depend on the masses of the involved quarks and the mixing angles between the Higgs fields and the right-handed up-type quarks, which rely on the $U(1)'$ charge assignment [67, 68]. After all the Yukawa couplings would be proportional to the quark masses responsible for the interactions so that we could ignore the Yukawa couplings which are not related to the top quark.

The number of relevant Higgs bosons participating in the top-quark pair production depends on the $U(1)'$ charge assignment and mixing angles. The relevant Yukawa couplings for the top-quark pair production can be written as

$$V = Y_{tu} \bar{u}_L t_R h + Y_{tu}^H \bar{u}_L t_R H + i Y_{tu}^a \bar{u}_L t_R a + h.c., \quad (4)$$

where h and a are the lightest neutral scalar and pseudoscalar Higgs bosons, and H is the heavier (second lightest) neutral Higgs boson. We assume that the Yukawa couplings of the other Higgs bosons are suppressed by

the mixing angles ‡.

In the Ref. [68], the explicit expressions are given in the $(u_i) = (0, 0, 1)$ case:

$$Y_{tu} = \frac{2m_t(g_R^u)_{ut}}{v \sin(2\beta)} \sin(\alpha - \beta) \cos \alpha_\Phi, \quad (5)$$

$$Y_{tu}^H = -\frac{2m_t(g_R^u)_{ut}}{v \sin(2\beta)} \cos(\alpha - \beta) \cos \alpha_\Phi, \quad (6)$$

$$Y_{tu}^a = \frac{2m_t(g_R^u)_{ut}}{v \sin(2\beta)}. \quad (7)$$

The $Y_{tt}^{(a)}$ couplings could be also large. But in this case, the s -channel contribution of the Higgs bosons to the production of the top-quark pair would be suppressed by the $Y_{qq}^{(a)}$ couplings of light quarks, which are proportional to m_q .

Finally, leptophobic and flavor-dependent chiral $U(1)'$ models are anomalous. The gauge anomalies can be easily canceled by adding extra chiral fermions: for example, one extra generation and two SM gauge vector-like pairs [68]. One of the fermions may be a good candidate for the dark matter and the Higgs boson could decay to two dark matters because of the mixing between the Higgs doublets and the SM singlet field Φ . If the branching ratio of the Higgs boson to the dark matters is large, the stringent constraints from the Higgs boson search at the LHC could be relaxed [67], and the Higgs boson of mass around 200 GeV is still viable because it could decay into a pair of CDM's.

III. PHENOMENOLOGY

A. Generalities and Inputs

In this section, we discuss phenomenology of our model described in the previous section. If new physics affects the top-quark pair production and could accommodate A_{FB}^t at the Tevatron, it must also be consistent with many other experimental measurements related with the top quark. In our models, both the Z' and Higgs bosons h and a contribute to the top-quark pair production through the t -channel exchange in the $u\bar{u} \rightarrow t\bar{t}$ process. As we discussed in the previous section, the Z' boson also contributes to the top-quark pair production through the s -channel exchange, which was ignored in Ref. [10].

As two extreme cases, one can consider the cases where only the Z' boson or Higgs boson h contributes to the top-quark pair production. Then, our models become

* We note that the relation is not valid for the other charge assignments.

† It is also true that one cannot write nonrenormalizable Yukawa interactions with the SM Higgs doublet only. It is essential to include the Higgs doublets with nonzero $U(1)'$ charges in order that one can write Yukawa couplings for the up-type quarks in this model.

‡ This assumption is not compulsory, since all the Higgs bosons might participate in the top-quark pair production in principle. We will keep only a few lightest (pseudo) scalar bosons in order to simplify the numerical analysis.

close to the simple Z' model of Ref. [10] or the scalar-exchange model of Ref. [40]. Unfortunately, these models cannot be compatible with the present upper bound on the same-sign top-quark pair production at the LHC in the parameter space which give rise to a moderate A_{FB}^t [68, 72, 73]. In our chiral $U(1)'$ models, the constraint from the same-sign top-quark pair production could be relaxed because of the destructive interference between the contribution from the Z' and those from Higgs bosons h and a . In particular, the contribution of the pseudoscalar boson a to the same-sign top-quark pair production is opposite to the other contributions.

In the two Higgs doublet model with the $U(1)'$ assignments to the right-handed up-type quarks, $(u_i) = (0, 0, 1)$, the s -channel contribution of the Z' exchange to the partonic process $u\bar{u} \rightarrow t\bar{t}$ is as strong as an t -channel contribution because of the relation $(g_R^u)_{ut}^2 = (g_R^u)_{uu}(g_R^u)_{tt}$ [68]. In the multi-Higgs doublet models (mHDMs) with other $U(1)'$ charge assignments (u_i) 's to the right-handed up-type quarks, the s -channel contribution could be small. In general, one can write $(g_R^u)_{uu}(g_R^u)_{tt} = \xi(g_R^u)_{ut}^2$, where ξ is a function of mixing angles and $0 \leq |\xi| \leq O(1)$. In the case of $m_{Z'} \geq 2m_t$, a resonance around the Z' mass for nonzero ξ would be observed in the $t\bar{t}$ invariant mass distribution. However, such a resonance has not been observed so far in the experiments [77, 78]. This would restrict the Z' mass to be much smaller than $2m_t$ for nonzero ξ .

The cross sections for the top-quark pair production at the Tevatron are $\sigma(t\bar{t}) = (7.5 \pm 0.48)$ pb at CDF [79] and $\sigma(t\bar{t}) = (7.56^{+0.63}_{-0.56})$ pb at D0 [80], respectively. At the LHC, the cross sections for the top-quark pair production are $\sigma(t\bar{t}) = (165.8 \pm 13.3)$ pb at CMS [81] and $\sigma(t\bar{t}) = (177 \pm 11)$ pb at ATLAS [82], respectively. In this work, we require that the cross section for the top-quark pair production is in agreement with the CDF result in the 1σ level, which has the least uncertainty. Another reason to use the Tevatron result for the check of our model is that the top-quark pair production at the Tevatron is more sensitive to new physics in the $u\bar{u} \rightarrow t\bar{t}$ process than at the LHC.

In the SM, the top quark dominantly decays into $W+b$. In our models, there are several flavor-changing vertices u_R-t_R-Z' , u_R-t_L-h , and u_R-t_L-a . If the Z' or Higgs bosons are lighter than the top quark, it could be dangerous because the branching ratio of the top quark to $W+b$ is significantly altered. We assume that the pseudoscalar Higgs boson a is heavier than the top quark and the branching ratio of the exotic decay of the top quark such as $t \rightarrow Z'u, hu$ is less than 5%. We find that the exotic decay mode of the top quark can be suppressed, if we choose $\alpha_x \equiv ((g'g_R^u)_{ut})^2/(4\pi) \lesssim 0.012$ for $m_{Z'} = 145$ GeV and $Y_{tu} \lesssim 0.5$ for $m_h = 125$ GeV.

Furthermore, such large FCNCs could generate the same-sign top-quark pair production through the t -channel diagram in the $uu \rightarrow t\bar{t}$ process, which is forbidden within the SM [73]. The CMS Collaboration announced the upper bound on the cross section for the

same-sign top-quark pair production: $\sigma^{tt} < 17$ pb at 95% CL. with a luminosity of 35 pb^{-1} [71], while the limit on the cross sections at ATLAS with a luminosity of 1.04 fb^{-1} are $\sigma^{tt} < 2$ pb at 95% CL. by using an optimized event selection for the Z' model and $\sigma^{tt} < 4$ pb at 95% CL. by using more inclusive selection, respectively [72]. We use the latter limit in this work.

In numerical analysis, we take the top-quark mass to be $m_t = 173$ GeV. For a parton distribution function we use CTEQ6m with the renormalization and the factorization scale equal to $\mu = m_t$ [83]. In order to take into account the QCD radiative correction which is unknown as of now for the model under consideration, we use the K factor obtained in the perturbative QCD calculations: namely, $K = 1.3$ for the Tevatron and $K = 1.7$ for the LHC by assuming the same K factor in the new physics model. The center-of-momentum energy \sqrt{s} is 1.96 TeV at the Tevatron and 7 TeV at the LHC, respectively. In the previous works [67–69], we did not consider the SM NLO contribution to A_{FB}^t , but in this work we take into account its contribution to A_{FB}^t by using the approximated formula $A_{\text{FB}}^t \simeq A_{\text{FB}}^{t,\text{SM}} + \delta A_{\text{FB}}^t/K$, where the first term denotes A_{FB}^t at the SM NLO and the second one corresponds to the contribution from the new physics. We also use the approximated formula $A_C^y \simeq A_C^{y,\text{SM}} + \delta A_C^y/K$.

B. $m_{Z'} = 145$ GeV cases

In this subsection, we discuss the light Z' cases with $m_{Z'} = 145$ GeV. The scalar Higgs boson h is chosen to be heavier than the top quark in order to suppress the branching ratio of the exotic decay of the top quark. In the two Higgs doublet model (2HDM), ξ is fixed to be 1 so that the s -channel exchange of the Z' boson is as strong as the t -channel exchange. On the other hand, in the mHDM cases, $|\xi|$ would be between 0 and $O(1)$ depending on the mixing angles between scalar bosons. In the case of $\xi \simeq 0$, the s -channel contribution of Z' would be negligible.

In this work, we consider two cases, $\xi = 1$ and $\xi = 0$ for illustration.

1. $\xi = 1$ case

Here, we consider the case with $\xi = 1$, so that one has the relation $(g_R^u)_{uu}(g_R^u)_{tt} = \xi(g_R^u)_{ut}^2$. Then the s -channel Z' exchange contribution is compatible with the t -channel Z' exchange contribution, and both should be kept in the phenomenological analysis.

The other model parameters are chosen in the following ranges: $180 \text{ GeV} \leq m_h, m_a \leq 1 \text{ TeV}$, $0.005 \leq \alpha_x \leq 0.012$, and $0.5 \leq Y_{tu}, Y_{tu}^a \leq 1.5$ with the condition $Y_{tu} \leq Y_{tu}^a$ [see Eq.s (5)-(7)]. In Fig. 1 (a), we show the scattered plot for A_{FB}^t at the Tevatron and σ^{tt} at the LHC at 7 TeV in unit of pb for $m_{Z'} = 145$ GeV. The red points satisfy the cross section for the top-quark pair

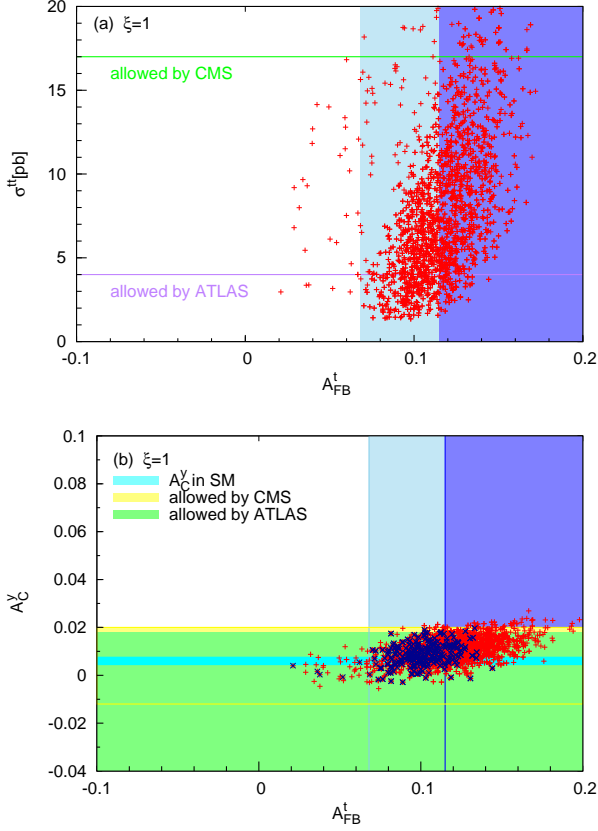


FIG. 1: The scattered plots for (a) A_{FB}^t at the Tevatron and $\sigma^{t\bar{t}}$ at the LHC in unit of pb, and (b) A_{FB}^t at the Tevatron and A_C^y at the LHC for $m_{Z'} = 145$ GeV and $\xi = 1$. In (b), the blue points satisfy the upper bound on the same sign top pair production from ATLAS: $\sigma^{t\bar{t}} < 4$ pb.

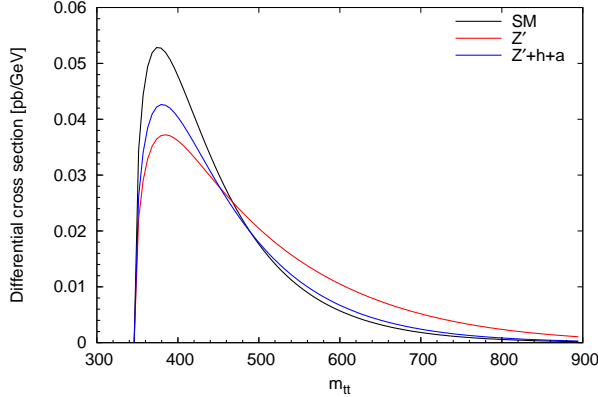


FIG. 2: The invariant mass distribution of the top-quark pair at the Tevatron in the SM, Z' model, and chiral $U(1)'$ model.

production at the Tevatron in the 1σ level. The regions below horizontal lines are the allowed regions from the limits on $\sigma^{t\bar{t}}$ at CMS and ATLAS, respectively. As dis-

cussed in Ref. [72], the t -channel exchange models with a Z' or scalar boson only are disfavored by the constraint on $\sigma^{t\bar{t}}$ at the LHC. But in our model, this strong constraint could be relaxed due to the destructive interferences between the Z' and Higgs boson t -channel exchange diagrams.

This is one of important lessons in our study for the flavor-dependent chiral $U(1)'$ model. It is often argued that a certain model is excluded or disfavored from experiments by assuming that only one coupling is dominant and ignoring other contributions. However, if a complete model with all the necessary ingredients is considered, the stringent constraint from experiments might be relaxed.

In Fig. 1 (a), the blue and skyblue bands are consistent with A_{FB}^t in lepton+jets channels at CDF in the 1σ and 2σ levels, respectively. We note that there exists a favored region even if we use the most stringent constraint on $\sigma^{t\bar{t}}$ at ATLAS. Our model with the light Z' boson could be disfavored, if the experimental upper bound on the same-sign top-quark pair production cross section becomes below ~ 1 pb at the LHC in the near future.

In Fig. 1 (b), we show the scattered plot for A_{FB}^t at the Tevatron and A_C^y at the LHC at 7 TeV for $m_{Z'} = 145$ GeV. The yellow and green regions are experimental bounds on A_C^y in the 1σ level at CMS and at ATLAS, respectively. The horizontal cyan band is the SM prediction for the charge asymmetry A_C^y . The blue and skyblue bands are same as in Fig. 1 (a). The red dots in Fig. 1 (b) satisfy the $t\bar{t}$ production cross section at the Tevatron within 1σ and the blue dots satisfy the experimental limit $\sigma^{t\bar{t}} < 4$ pb on the cross section for the same-sign top-quark pair production at the LHC as well as the $t\bar{t}$ production cross section at the Tevatron within 1σ . The Z' or W' exchange model in the t -channel predicts a large positive A_C^y , which might be inconsistent with the current data at the LHC [75]. The light Z' case in our model is in good agreement with the data for A_C^y at the LHC in some parameter regions as shown in Fig. 1 (b) due to the additional contributions from the neutral Higgs bosons h and a .

The invariant mass distribution of the top-quark pair (especially in the large invariant mass region) could be a good discriminator of the models for A_{FB}^t [10]. In Fig. 2, we show the invariant mass distribution of the top quark pair produced at the Tevatron. The black curve is the SM case at leading order (LO). The red curve corresponds to the original Z' model (without neutral Higgs bosons) with a large off-diagonal coupling for $m_{Z'} = 145$ GeV and $\alpha_x = 0.029$ [10]. In this case, the model overestimates (underestimates) the SM predictions in the large (small) invariant mass region. This is a typical feature of the model with a large t -channel contribution to the $q\bar{q} \rightarrow t\bar{t}$. Finally, the blue curve is the chiral $U(1)'$ model (with the contributions of Z' , h and a all included) with the following parameters: $m_{Z'} = 145$ GeV, $m_h = 180$ GeV, $m_a = 250$ GeV, $\alpha_x = 0.005$, $Y_{tu} = 1$, and $Y_{tu}^a = 1.1$. The

general feature is similar to the Z' model, but the prediction of the chiral $U(1)'$ model becomes much closer to the LO SM prediction because of the destructive interferences between the contributions from the Z' and Higgs bosons. This is another benefit of our model, since the current measurement of the $t\bar{t}$ invariant mass distribution is not much deviated from the SM prediction. For more detailed comparison, one must include the NLO predictions in the SM and each new physics model, which is not available yet in the literature and also beyond the scope of this paper. However, we could conclude that the large deviation of the $t\bar{t}$ invariant mass distribution in the original Z' model can be significantly improved by including the contributions of Higgs bosons h and a .

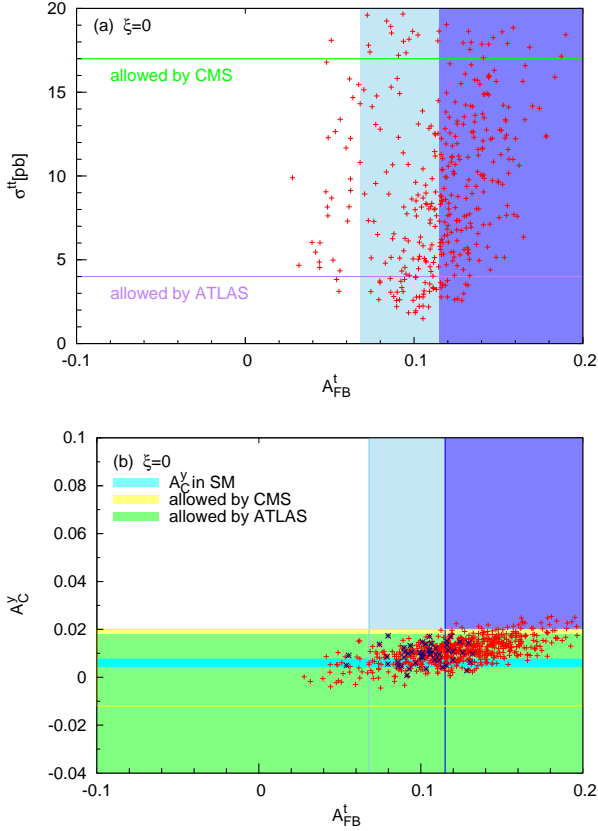


FIG. 3: The scattered plots for (a) A_{FB}^t at the Tevatron and $\sigma^{t\bar{t}}$ at the LHC in unit of pb, and (b) A_{FB}^t at the Tevatron and A_C^y at the LHC for $m_{Z'} = 145$ GeV and $\xi = 0$.

2. $\xi = 0$ case

Now, let us discuss another extreme case with $\xi = 0$: namely, $(g_R^u)_{uu}(g_R^u)_{tt} = 0$. Then, the Z' boson contributes to the top-quark pair production through only its t -channel exchange. And there would be no strong constraints from dijet or $t\bar{t}$ resonance searches. We vary

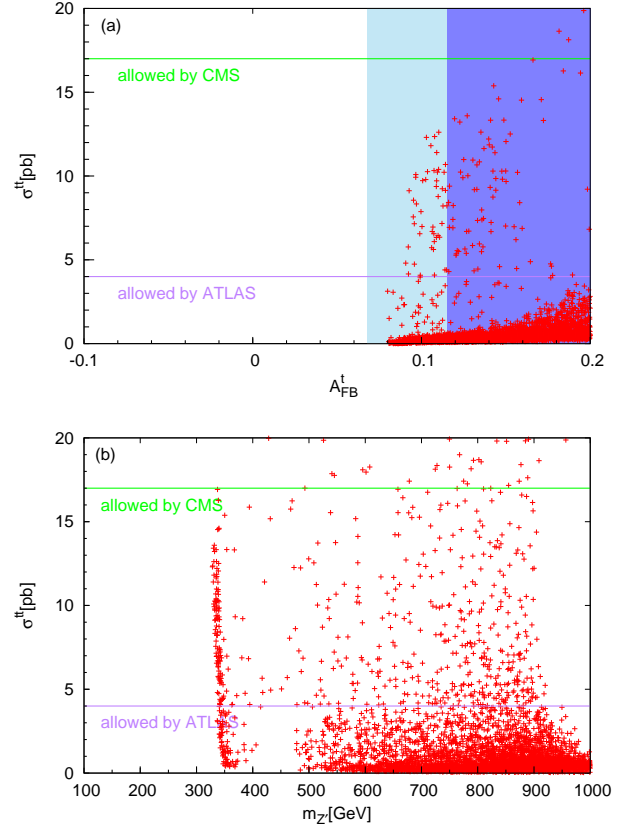


FIG. 4: The scattered plots for (a) A_{FB}^t at the Tevatron and $\sigma^{t\bar{t}}$ at the LHC in unit of pb, and (b) $m_{Z'}$ in unit of GeV and $\sigma^{t\bar{t}}$ at the LHC in unit of pb for $m_h = 125$ GeV.

other model parameters in the same ranges as in the $\xi = 1$ case of section III B 1. In Fig. 3, we present the scattered plots (a) for A_{FB}^t at the Tevatron and $\sigma^{t\bar{t}}$ at the LHC in unit of pb and (b) for A_{FB}^t at the Tevatron and A_C^y at the LHC, where we use the same legends as in Fig. 1. The general feature is basically the same as in Fig. 1. We find that there is a parameter space where our predictions are in good agreement with the current experimental constraints in case of $\xi = 0$. This would also imply that there would be some parameter regions satisfying the empirical data in the range $0 \leq \xi \leq 1$.

C. $m_h = 125$ GeV within 2HDM ($\xi = 1$)

In the previous works [67–69], only the relatively light Z' case was considered, since we were also interested in accounting for the Wjj excess at CDF in the same model. Because the CDF Wjj excess was not confirmed by the D0 Collaboration, the motivation for $m_{Z'} \simeq 145$ GeV becomes weaker. On the other hand, both ATLAS and CMS announced discovery of new boson of mass around 125 GeV [84, 85], whose properties are quite similar to those of the SM Higgs boson within experimental uncer-

tainties.

Therefore in this subsection, we consider $m_h = 125\text{ GeV}$ motivated by the recent data [84, 85], assuming the Z' mass is set free. Other parameters are chosen in the following ranges: $180\text{ GeV} \leq m_{Z'} \leq 1.5\text{ TeV}$, $180\text{ GeV} \leq m_a \leq 1\text{ TeV}$, $0.005 \leq \alpha_x \leq 0.025$, $0.1 \leq Y_{tu} \leq 0.5$, and $0.1 \leq Y_{tu}^a \leq 1.5$ with the condition $Y_{tu} \leq Y_{tu}^a$ and $\xi = 1$. We note that the Yukawa coupling Y_{tu} is chosen to be less than 0.5 in order to satisfy the condition $\text{Br}(t \rightarrow \text{non-SM state}) \lesssim 5\%$. In Fig. 4 (a), we show the scattered plot for A_{FB}^t at the Tevatron and σ^{tt} in unit of pb at the LHC for the lightest Higgs boson mass $m_h = 125\text{ GeV}$. As in Fig. 1 (a), the red points satisfy the cross section for the $t\bar{t}$ production at the Tevatron within 1σ . Many points in the right-bottom seem to be in good agreement with the constraints from the top FB asymmetry at the Tevatron and the same-sign top pair production at the LHC. However, we find that the Z' mass for those points are in the range of $350\text{ GeV} \lesssim m_{Z'} \lesssim 1.2\text{ TeV}$ as shown in Fig. 4 (b). As we have discussed earlier, the s -channel diagram through the Z' exchange contributes to the $u\bar{u} \rightarrow t\bar{t}$ process for $\xi = 1$. This implies that in the $t\bar{t}$ invariant mass distribution there appears a sharp peak around the Z' boson mass, which has not been observed in experiments [77, 78].

If we choose $\xi = 0$ or the decay width of the Z' boson is sufficiently large, then the resonance peak may not be observed in experiments for $m_{Z'} > 2m_t$. In our $U(1)'$ model, the latter case cannot be realized. However, the former case might be possible for a certain mixing angles in the mHDMs. Therefore, we searched for the parameter space which is consistent with all the experiments by setting $\xi = 0$. However, we found no favored region in this case too. In particular, A_{FB}^t could not be accommodated with the CDF data in the 1σ level. However, if we search with more relaxed experimental constraints, for example, the 2σ level for A_{FB}^t , we find that there exist the favored region consistent with all the experiments.

D. More Higgs bosons included

Up to now, we have kept only the lightest scalar (h) and pseudoscalar (a) Higgs bosons, assuming other heavier Higgs bosons decouple from top physics because either they are very heavy or they have small Yukawa couplings. In this subsection, we will relax this assumption, and include the second lightest Higgs boson H in the analysis. For the completeness, one must consider all the Higgs bosons as well as the extra fermions, but it would be quite complicated and time-consuming since there are too many new parameters involved. We will be content with a simplified discussion of Higgs sector. In the following sections, we consider two cases $\xi = 1$ and $\xi = 0$ for illustration.

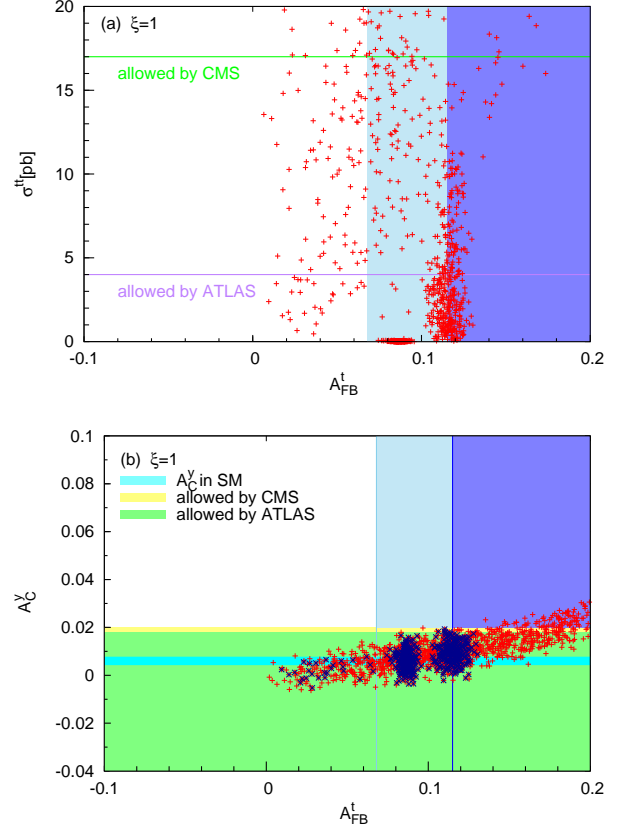


FIG. 5: The scattered plots for (a) A_{FB}^t at the Tevatron and σ^{tt} at the LHC in unit of pb, and (b) A_{FB}^t at the Tevatron and A_C^y at the LHC for $m_h = 125\text{ GeV}$ and $\xi = 1$, where the contribution of the second lightest Higgs boson H is included.

1. $\xi = 1$ case

Let us first consider the $\xi = 1$ case. If the second lightest scalar Higgs boson H has a flavor-changing coupling to the top quark like the lightest scalar Higgs boson h , there are four new particles Z' , h , H , and a that contribute to the top-quark pair production. We take the lightest Higgs boson mass to be $m_h = 125\text{ GeV}$ like in the previous case. The other parameters are taken to be in the following ranges: $160\text{ GeV} \leq m_{Z'} \leq 300\text{ GeV}$, $180\text{ GeV} \leq m_H, m_a \leq 1\text{ TeV}$, $0 \leq \alpha_x \leq 0.025$, $0 \leq Y_{tu} \leq 0.5$, and $0 \leq Y_{tu}^H, Y_{tu}^a \leq 1.5$, where m_H is the mass of the second lightest scalar Higgs boson and Y_{tu}^H is its Yukawa coupling to the u - t - H vertex. Note that the range of the Z' boson mass is chosen to avoid the constraints from the top quark decay and $t\bar{t}$ invariant mass distribution.

Figure 5 (a) shows the scattered plot for A_{FB}^t at the Tevatron and σ^{tt} at the LHC in unit of pb. The red points satisfy the cross section for the top-quark pair production at the Tevatron in the 1σ level. The horizontal lines are upper limits on the same-sign top-quark pair production at CMS and ATLAS, respectively. The blue and skyblue

regions are consistent with A_{FB}^t in the lepton+jets channel at CDF within 1σ and 2σ , respectively. We find that there exist some parameter regions which are in agreement with A_{FB}^t within 1σ and the upper limit on $\sigma^{t\bar{t}}$ at ATLAS. Thus the light Higgs boson with $m_h = 125$ GeV in our model could pass all the experimental constraints if the heavier scalar Higgs boson H contributes to the top-quark pair production.

In Fig. 5 (b), we show the scattered plot for A_{FB}^t at the Tevatron and A_C^y at the LHC. Each region on the figure denotes the same experimental constraint as on Fig. 1 (b). The red points in Fig. 5 (b) satisfy the $t\bar{t}$ production cross section at the Tevatron within 1σ and the blue points satisfy the experimental limit $\sigma^{t\bar{t}} < 4$ pb on the cross section for the same-sign top-quark pair production at ATLAS as well as the $t\bar{t}$ production cross section at the Tevatron within 1σ . The light Higgs boson case with $m_h = 125$ GeV could be in good agreement with the data for A_{FB}^t at the Tevatron and A_C^y at the LHC as shown in Fig. 5 (b) if more Higgs bosons are included. Furthermore, it is amusing that in this case the same-sign top-quark pair production at the LHC could be less than 1 pb as shown in Fig. 5 (a).

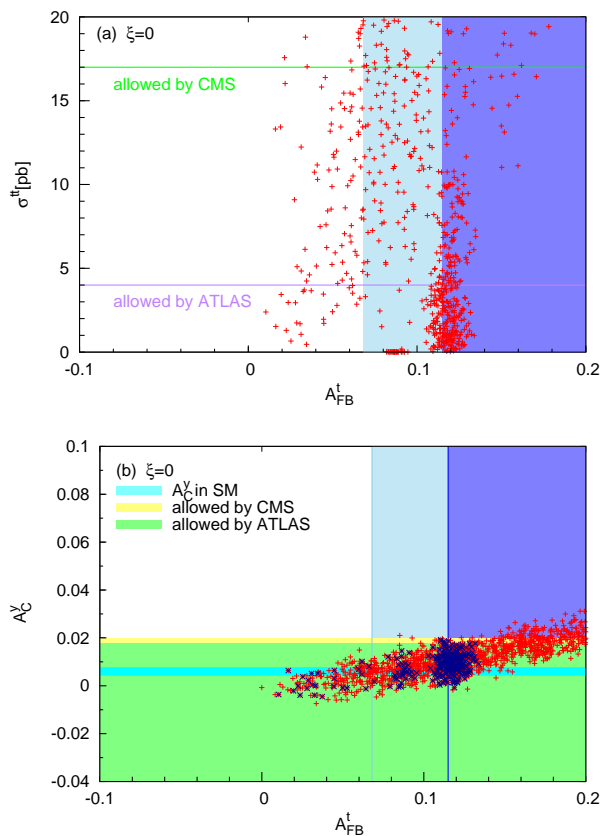


FIG. 6: The scattered plots for (a) A_{FB}^t at the Tevatron and $\sigma^{t\bar{t}}$ at the LHC in unit of pb, and (b) A_{FB}^t at the Tevatron and A_C^y at the LHC for $m_h = 125$ GeV and $\xi = 0$, where the contribution of the second lightest Higgs boson H is included.

2. $\xi = 0$ case

In this section, we consider the $\xi = 0$ case, where the s -channel contribution of the Z' boson to the top-quark pair production is negligible. The other model parameters are varied in the same ranges as in the $\xi = 1$ case of Sec. IIID 1. In Fig. 6, we show the scattered plots (a) for A_{FB}^t at the Tevatron and $\sigma^{t\bar{t}}$ at the LHC in unit of pb and (b) for A_{FB}^t at the Tevatron and A_C^y at the LHC, where all the legends on the figure are the same as those on Fig. 5. As in the case of $\xi = 1$, we find some parameter regions satisfying all the experimental constraints. Like the light Z' case, one would find the allowed regions in the whole range of $0 \leq \xi \leq 1$.

E. Summary

In this section, we examined three different cases of chiral $U(1)'$ models proposed by the present authors [67–69]: (i) the light Z' model with $m_{Z'} = 145$ GeV and h and a being heavier than the top quark, (ii) the light scalar Higgs model with $m_h = 125$ GeV and Z' and a being heavier than the top quark, and (iii) the light scalar Higgs model with Z' , H , and a , where $m_h = 125$ GeV, $m_{Z'} \geq 160$ GeV and $m_{H,a} \geq m_t$.

In the first and third cases we can find the parameter regions which are in good agreement with all the experimental constraints in the 1σ level, but in the second case the accommodation is possible only in the 2σ level. Except the above cases, there can exist other cases which might be consistent with experiments. For instance, one can consider the light Z' and light Higgs model. Suppose that $m_{Z'} = 145$ GeV and $m_h = 125$ GeV, but the lightest Higgs boson weakly couples to the top quark. Then, we can apply the case (i) to this model by assuming that the lightest Higgs boson has a negligible off-diagonal Yukawa coupling and the second Higgs boson has a large off-diagonal Yukawa coupling.

IV. CONCLUSIONS

A_{FB}^t reported by CDF and D0 Collaborations has been one of the hottest issues in particle physics phenomenology during last four years. Assuming that the observed deviation in A_{FB}^t might be a signal of new physics, a number of models have been proposed to explain the observed A_{FB}^t . Some models were already disfavored by experiments, and other models might be verified at the LHC soon.

In the Refs. [67–69], the present authors have proposed complete realistic models with $U(1)'$ flavor symmetry, where only right-handed up-type quarks are charged flavor-dependently, in order to avoid the strong constraints on FCNC. Then, realistic Yukawa interactions were constructed by adding extra Higgs doublets which are charged under $U(1)'$ flavor symmetry. Then, it was

found that there arise new additional FCNC Yukawa couplings involving the light (pseudo)scalars. Surprisingly, the interference between the extra gauge boson and scalar bosons can relax the bound from the same-sign top process at LHC, and we found that the light Z' scenario can be revived.

In this work, we reexamined the $U(1)'$ models, including the updated results on the same-sign top-quark pair productions at the LHC, and investigated the top charge asymmetry at LHC. We found that there are parameter regions in the light Z' model with scalar and pseudoscalar Higgs bosons, which are consistent with empirical data, for example, for $m_{Z'} = 145$ GeV, $m_h \sim 200$ GeV, and $m_a \sim 250$ GeV. However, if the same-sign top-quark pair production rate turns out to be smaller than ~ 1 pb, this model with the $U(1)'$ and light Z' will be likely excluded.

Furthermore, the recent Higgs search at the LHC, which has a tentative excess in about 125 GeV mass region, also constrains our scenario strongly. We also analyzed the light Higgs boson case. In the case of the light Higgs boson case with Z' , H , and a , where $m_h = 125$ GeV, $m_{Z'} \geq 160$ GeV and $m_{H,a} \geq m_t$, there exist parameter spaces which can be in good agreement with all the empirical data within 1σ . Even though the upper bound on the same-sign top-quark pair production rate at the LHC becomes less than 1 pb, we can find some parameter regions consistent with the experimental data. However, in the case that only the lightest Higgs boson h ($m_h = 125$ GeV), pseudoscalar Higgs boson a ($m_a \geq m_t$), and Z' ($m_{Z'} \geq m_t$) contribute to the top-quark pair production, we could not find the favored parameter regions which can be accommodated with the present experiments in the 1σ level. In this case, we must relax the experimental bound to the 2σ level, or consider the light Z' model where the lightest Higgs boson (~ 125 GeV) has a negligible off-diagonal Yukawa coupling and the second lightest Higgs boson has a large off-diagonal Yukawa coupling.

Usually the original Z' model is considered having been disfavored, independently by the stringent upper bound on the same-sign top-quark pair production cross sections and the shape of $m_{t\bar{t}}$ spectrum at high $m_{t\bar{t}}$ region, as well as the null results of the charge asymmetry at the LHC. However, our current study and the previous analyses [67, 68] show that these conclusions are too premature, since extra Higgs doublets charged under $U(1)'$ are required for realistic Yukawa couplings and they usually contribute to the top physics. When we extend the Higgs sector and generate the top quark mass correctly as presented in Refs. [67, 68], there appear the neutral Higgs mediated FCNC in the up-quark sector, which contributes to all the observables related with the top FB asymmetry at the Tevatron and the charge asymmetry at the LHC. It is neither consistent nor complete to do phenomenological analysis, keeping only the Z' contribution with the physical top mass equal to the experimental value. Our predictions on the correlations among A_{FB}^t , σ_{tt} and A_C^g are completely different from the results in the

literature (see Ref. [46], for example). These comments about new Higgs doublets would apply to other models where new spin-1 vector bosons have chiral couplings to the SM fermions.

Also it should be emphasized that there is no mathematical limit where one can integrate out the $U(1)'$ -charged new Higgs doublets assuming they are very heavy, and keep only the light Z' . The reason is that the would-be Goldstone bosons eaten by the SM W_L and Z_L are shared among all the Higgs doublets with nonzero VEV's. Since these massless components are also reside in the $U(1)'$ -charged Higgs doublets, one can not integrate them out. Also there would be the problem with the realistic Yukawa couplings for the up-type quarks if one would have integrated them out. On the other hand, one can consider the opposite limit where the Z' boson is very heavy and can be integrated out. Then the low energy effective theory would be multi-Higgs doublet models with some FCNC interactions to the up-type quarks. Eventually our model may be excluded by the future experiments on the observables we studied in this paper or another observables. However the Z' model with $U(1)'$ -flavored Higgs doublets are still viable explanations to the top FB asymmetry at the Tevatron, without conflict with the same-sign top-quark pair productions, the $m_{t\bar{t}}$ distributions, or the charge asymmetry at the LHC, unlike the common belief.

Finally, it should be mentioned that our study is not complete yet, because there are extra fields which we simply assumed to be subdominant for physics of A_{FB}^t . In this paper, we included the heavier neutral scalar bosons and could achieve the large A_{FB}^t without too large same-sign top-quark pair cross section. We demonstrated the lighter neutral scalar could correspond to the excess at LHC. Such heavier neutral scalar bosons should also be constrained by the Higgs search at the LHC and Tevatron.

Note Added

While we are finalizing this paper, both the ATLAS and CMS collaborations have announced the discover of a Higgs-like scalar boson with ~ 125 GeV mass [86, 87]. They have observed a rather larger excess in the $h \rightarrow \gamma\gamma$ channel and smaller signals in the $h \rightarrow WW/ZZ$ channels. If the branching ratios settle down at the present values, our models will severely be constrained. We anticipate further results of this Higgs-like scalar boson.

Furthermore, the CMS collaboration has announced more stringent bound on the cross section for the same-sign top-quark pair production at the LHC: $\sigma^{tt} \leq 0.39$ pb at 95% confidence level [88, 89]. This strong bound would exclude the light Z' boson case. However, we note that the light scalar Higgs boson model with Z' , H , and a , where $m_h = 125$ GeV, $m_{Z'} \geq 160$ GeV and $m_{H,a} \geq m_t$ might be in agreement with this upper bound in a certain parameter space.

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